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SPACE, TELECOMMUNICATIONS AND RADIOSCIENCE LABORATORY

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A REAL TIME INDEX OF GEOMAGNETIC BACKGROUND NOISE FOR THE M.A.D. FREQUENCY RANGE

by
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An index of geomagnetic activity in the upper part of the ultra low frequency (ULF) range (less than 4.55 Hz) has been developed. This index will be referred to as the MA index (magnetic activity index). The MA index is prepared every half hour and is a measure of the strength of the geomagnetic activity in the Pc 1 - Pc 3 pulsation frequency range during that half hour period. Activity in the individual Pc pulsation ranges can also be measured, if desired. The index is calculated from the running average of the full-wave rectified values of the band pass filtered geomagnetic signals and thus it

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provides a better indication of the magnitude of these band pass filtered magnetic pulsations than does the ap index, for example. Daily variations of the band pass filtered magnetic signals are also better captured by the MA index.

A signal processing system was built to implement the MA index. The system consists of an HP-85 desktop computer and an index generation system. The index generation section is microprocessor-based and is capable of computing the indices at regular intervals. These indices are then recorded by the HP-85.

To test this system we used analog tape recordings of wide-band geomagnetic signals, ~~that were previously~~ recorded at Stanford. The indices for these tapes are presented in the form of plots, together with a comparison with the ap indices for the same time intervals. The MA index shows the daily variation of the geomagnetic signals quite clearly during times when there is strong activity, i.e., when the ap index values are large. Because impulsive signals, such as lightning discharges, tend to be suppressed in the averaging process, the MA index is insensitive to impulsive noise. It is found that the time variation of the MA index is in general markedly different from the variation of the ap index for the same time intervals.

A REAL TIME INDEX OF GEOMAGNETIC BACKGROUND NOISE FOR THE M.A.D. FREQUENCY BAND

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An index of geomagnetic activity in the upper part of the ultra low frequency (ULF) range (less than 4.55 Hz) has been developed. This index will be referred to as the MA index (Magnetic Activity index). The MA index is prepared every half hour and is a measure of the strength of the geomagnetic activity in the Pc 1 - Pc 3 pulsation frequency range during that half hour period. Activity in the individual Pc pulsation ranges can also be measured, if desired. The index is calculated from the running average of the full-wave rectified values of the band pass filtered geomagnetic activity and it provides an accurate measure of the magnitude of this activity, unlike the standard geomagnetic activity indices A_{Fr}, Ap, ap, or Kp, for example. Daily variations of the band pass filtered magnetic signals are also better captured by the MA index.

A signal processing system was built to implement the MA index. The system consists of an HP–85 desktop computer and an index generation system. The index generation section is microprocessor-based and is capable of computing the indices at regular intervals. These indices are then recorded by the HP–85.

To test this system we used analog tape recordings of wide-band geomagnetic signals that were previously recorded at Stanford. The indices for these tapes are presented in the form of plots, together with a comparison with the *ap* indices for the same time intervals. The MA index shows the daily variation of the geomagnetic signals quite clearly during times when there is strong activity, *i.e.*, when the *ap* index values are large. Because impulsive signals, such as those generated by lightning discharges, tend to be suppressed in the averaging process, the MA index is insensitive to impulsive noise. It is found that the time variation of the MA index is in general markedly different from the variation of the *ap* index for the same time intervals.

TABLE OF CONTENTS

I. INTRODUCTION

This report describes the results of a project to derive an index of geomagnetic activity, or geomagnetic background noise, in the frequency range of 0.04 Hz to 2.0 Hz. This frequency range lies in the upper part of what is conventionally referred to as the ultra low frequency (ULF) range, and it corresponds closely to the range normally used for Magnetic Anomaly Detection (M.A.D.). The desired index, which we will refer to as the MA index (Magnetic Activity index), is to be prepared in real-time by using automatic data-processing equipment, and is to be updated by using the same data-processing equipment.

In the current method of operation, the M.A.D. frequency range may be subdivided (to a limited extent) by the operator of the M.A.D. equipment and the sensitivity of the system response to the magnetic field fluctuations within the chosen frequency range can also be adjusted. Details of these adjustments are described in the *Lockheed Orion Service Digest* [1972], among other sources. The purpose of the adjustments is to reduce the influence of the background geomagnetic noise on the sensitivity of the magnetic detection system and to help it function under a wide variety of different states of activity. Given this flexibility, the full capability of an M.A.D. system can only be realized if information is available to the M.A.D. system operator that will provide guidance as to what sub-band of the 0.04 - 2.0 Hz range to use, or what sensitivity setting would be most appropriate given a particular level of geomagnetic activity. This information may well be critical to the effectiveness of the operations, especially during times when strong geomagnetic activity exists in a limited frequency band. Thus, there needs to be a measure available for the strength of the geomagnetic noise in the overall M.A.D. band, which is the most basic requirement, together with further measures of the noise in possible sub-bands of interest.

At the present time the U.S. Navy routinely uses the A_{Fr} and Ap indices of geomagnetic activity as indicators of the likely level of geomagnetic noise in the overall M.A.D. band, and no attempt is made to sub-classify the noise further into specific frequency ranges. In addition to the A_{Fr} and Ap indices, which are daily indices and thus do not rapidly respond to sudden changes in activity, the three-hourly K indices from the Boulder geomagnetic observatory are available to interested users, both over the telephone and by way of the WWV and WWVH radio broadcasts. However, these latter indices are not routinely available to the U.S. Navy Fleet operators, who receive only the "alpha indices" A_{Fr} and Ap (both current estimates and predictions for a few days ahead) by way of transmissions originating at the Fleet Numerical Oceanographic Center at Monterey, California.

While the A_{Fr} and Ap indices, or the closely related K indices, can provide a useful indication of geomagnetic activity in the M.A.D. band on occasion [*Brennan and Smits,* 1975], they do not do so reliably [*Ochadlick,* 1976; *Schweiger,* 1982]; nor would we expect them to do so since, as pointed out by *Mayaud* [1980], the A- and K-indices are most sensitive to activity with periods of the order of a few hours or more, *i.e.*, to periods much longer than those included in the M.A.D. range.

A presentation describing the unsuitability of the A_{Fr} and Ap indices for the M.A.D. application and proposing the derivation of an index of geomagnetic activity specific to the M.A.D. band was given by one of the authors at the First International Symposium of the Society of MADmen in Washington, D.C., during June 14-16, 1982 [*Fraser-Smith and Heinz,* 1982]. Because of its relevance to the present report, the text of the presentation is reproduced in Appendix B.

The MA index we have developed is significantly different from the A_{Fr} and Ap indices. As described in Appendix B, the A-indices are range indices based on the size of the difference between the maximum and minimum levels of geomagnetic activity during a 3-hour period, whereas the MA index measures the average magnitude of the activity in a half-hour period.

The M.A.D. frequency range, 0.04 to 2.0 Hz, covers either the whole or part of the frequency range for four categories of geomagnetic pulsations. These are:

1. Pc 1 pulsations (0.2 to 5 Hz; periods 0.2 to 5 seconds).
2. Pc 2 pulsations (0.1 to 0.2 Hz; periods 5 to 10 seconds).
3. Pc 3 pulsations (0.022 to 0.1 Hz; periods 10 to 45 seconds).
4. Pi 1 pulsations (0.025 to 1 Hz; periods 1 to 40 seconds).

Thus, it is expected that the MA index will indicate the extent of geomagnetic activity present in these four categories. There is no reason why versions of the MA index applicable to each of the pulsation ranges can not be prepared as well, but this specialization will not be undertaken until the basic MA index is being computed routinely. It may also be possible to use the observed MA indices to predict future indices, using the techniques described by *Fraser-Smith* [1980, 1981], and this will be explored when the system is fully functional.

To implement the MA index, it was decided to design a stand-alone signal processing system. A stand-alone system would be one which, when properly configured, would not require any operator intervention. Consequently, this system had to be capable of initiating data collection from several analog channels, processing this information, and then generating various parameters related to these signals.

An important consideration was to have a compact system. This would make it feasible to have similar self contained systems located in various geographic locations, with each one performing independent signal processing tasks. These independent units could then communicate with a central facility and transmit their recorded indices indicating the state of the geomagnetic activity at their particular locations for further processing.

It was decided to perform the index generation and the recording of the indices in a parallel manner. This would require two independent data-processing units, one for index generation and one for the recording of indices. The two units would regularly exchange information, but otherwise each should be intelligent enough to perform their required tasks. The main advantage of the parallel scheme would be that the overall system could operate as fast as the *slowest* of the two processes. This limiting process was observed to be the index generation section, and this was expected because the index generation process had to sample a full half hour of data before generating an MA index, whereas the recording process could accomplish its task in a fraction of that time.

Thus, we decided that a small computer would be ideal for the recording of indices, and for the index generation system a microprocessor based unit seemed most appropriate.

2. THE MA INDEX

The basic idea behind this new index of geomagnetic activity is quite simple. We wanted an index which related to the "average" magnitude of the band pass filtered geomagnetic signals in the 0.04 Hz to 2.0 Hz band during the interval of interest. It was decided to make the rate of index generation to be half hourly. This should therefore give us a finer subdivision of time compared to the currently available three hourly *ap* indices.

There are various ways of calculating the "average" of a time signal. For example, one could find the average power of the signal, or perhaps the d.c. value of the signal, *etc*. For reasons of simplicity of implementation, we decided to base our indices on the d.c value of the signal for every half hour period. Of course, for a zero biased signal, a d.c. value of about zero would necessarily be attained at all times. To get around this problem it was decided to first full-wave rectify the signal and then find the average value of the signal every half hour.

One final point that still had to be decided was the sampling rate. First, we note that by the Nyquist criteria we need to sample at the rate of twice the highest frequency component present in the signal we're studying. Let us say that the highest frequency of interest for us is 5 Hz. Full-wave rectification is a nonlinear operation which introduces higher frequency components in the signal. For example, a 5 Hz sine wave will be rectified such that it has a fundamental frequency of 10 Hz and also frequency components of integer multiples of 10 Hz. If we decide to be satisfied with only capturing this 10 Hz fundamental then we'll need to sample at a rate of at least 20 Hz.

There are two interesting issues introduced here. The first one concerns the determination of the sampling frequency. The idea of Nyquist rate applies to the case when one wants to recover the sampled signal fully. Here we are forming a running sum of the sampled values and do not want to recover the signal. Thus, it may not be critical whether aliasing occurs or not. The second issue concerns the effects of the non-linear rectification on the sampling frequency. Given that the full-wave rectification process introduces an infinite set of frequencies, one either has to make a judgement so as how fast to sample or this choice can be made by hardware or software limitations.

In summary, therefore, the MA index generation process would have to perform the following three steps in order to obtain each index:

1. Sample the band pass filtered geomagnetic signal at a sufficiently high rate.

2. Keep a running sum of the sampled values for half an hour.

3. Divide the final sum by the number of samples taken during that half hour to obtain the MA index.

3. THE SIGNAL PROCESSING SYSTEM

3.1. HARDWARE

The hardware built for this project consists of a microprocessor-based index generation system. The index generation system periodically interacts with a small desktop Hewlett Packard computer (HP–85). The HP computer is used to initialize the index generation system and it regularly receives indices from the index generation section. The index generation system samples the full-wave rectified geomagnetic signal for a period of half an hour and transmits the average of those samples to the HP–85.

The index generation system is run by an Intel 8085A microprocessor. The main program for the microprocessor is burnt into ROM. The microprocessor controls an 8-bit analog to digital converter and various I/O ports. The I/O ports control the sample and hold circuits and also the address selection of an analog multiplexer.

The microprocessor is also in charge of transmitting the indices to the HP–85 computer. This transmission is done across an IEEE-488-1978 (HPIB) bus, and the microprocessor uses IEEE-488-1978 talker/listener chips to implement the specific bus protocols.

A further description of the index generation hardware and the experimental set-up is provided in the appendix.

3.2. SOFTWARE

As was stated earlier, the software for all of the operations of the index generation system is burnt into ROM. The program first waits to receive two bytes of data from the HP–85, which determine the frequency at which it will be sampling the geomagnetic signals. It then waits to output a status byte to the HP–85 computer. The instant this byte is sent to the HP–85 the microprocessor begins the data collection process. Thus, the HP–85 can control the beginning time of the index generation by deciding when to request the status byte.

It was decided to keep the number of samples taken during a half hour to a power of two. Consequently, to find the average value of the running sum (by dividing the running sum by the number of samples added) it would only be necessary to shift the bits in a register. This would be faster than implementing a division algorithm. Therefore, the number of samples taken in half an hour was fixed at $2^{15} = 32,768$.

The upper limit of the sampling frequency of this system is determined by the number of instructions the microprocessor has to execute between analog to digital conversions. This upper bound was experimentally found to be about 8000 Hz. On the other hand, the lower limit of the sampling frequency is determined by the number of bits of a divide counter. This lower limit is 178 Hz.

4. THE EXPERIMENTAL SET-UP

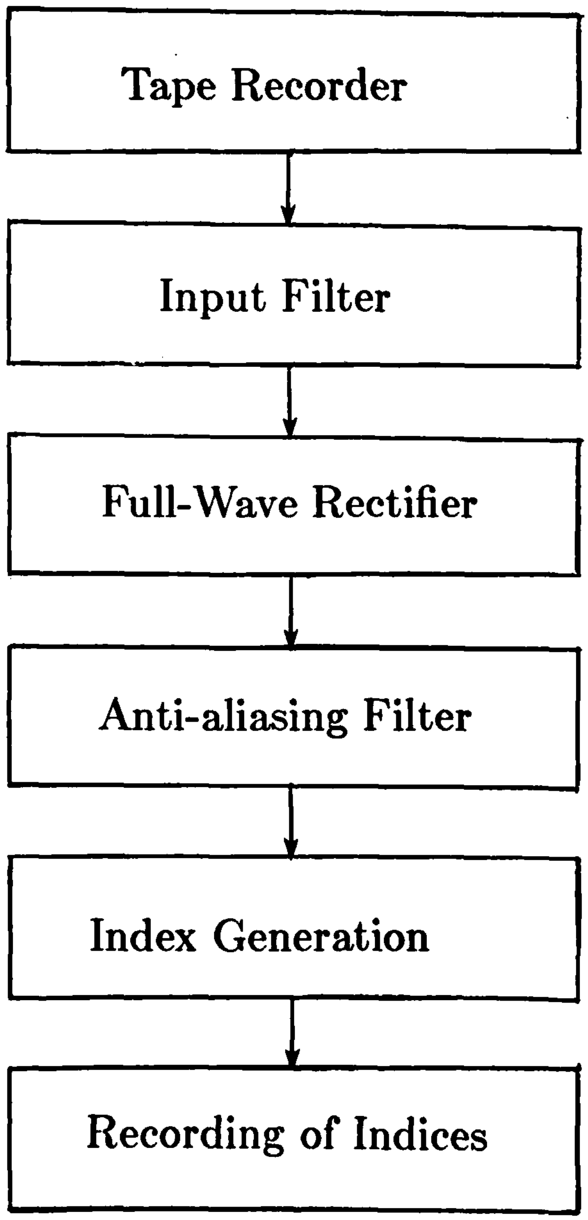
The experimental setup of this project was essentially as described above, but with one small change. The analog tapes of geomagnetic signals in our archives were recorded at a tape speed of about 0.03 inches/sec. However, these tapes were played back into the MA index generating system at a speed of 7.5 inches/sec. There was therefore a speed-up factor, SF, of approximately 250 introduced, which increased all the frequencies by the same factor. Note that this speed-up factor varied slightly between tapes and so the exact factor was calculated by checking hourly time and frequency calibration signals on each analog tape. The sampling rate of the index generation system was therefore readjusted for each tape. Since it was decided to sample 32,768 samples for every half hour of magnetic signals, it can be seen that the required sampling rate was

$$f_s = (SF)(32,768/1800)$$

The "effective" sampling rate of our system (not including the speed-up factor) is calculated to be 32,768/1800=18.2 Hz. Therefore, if we only consider the fundamental frequency of the full-wave rectification, we can see that we are sampling at a rate to capture at most a 18.2/4=4.55 Hz signal of a single sine wave.

A block diagram of the overall system is presented in the next page, and a description of the individual blocks follows on the following page.

System Block Diagram



5. SYSTEM DESCRIPTION

1. Tape Recorder:

The tape recorder was used to play back previously recorded analog tapes of band pass filtered geomagnetic signals. These tapes were recorded at Stanford, and they contain wide-band geomagnetic signals. The tapes were recorded at a speed of about 0.03 inches/sec, and thus, there is a speed-up factor of about 250 when playing back at a speed of 7.5 inches/sec. For example, half hour of recorded time corresponds to 7 seconds of tape at 7.5 inches/sec.

2. Input Filter:

The input filter is a Krohn-Hite eight-order Butterworth filter which can be configured as a low pass or a high pass filter. This gives a limitied capability of selecting certain range of frequencies as the input to the full-wave rectifier stage.

3. Full-Wave Rectifier:

The filtered signal going into this stage has a d.c. bias of 0 volts. This signal is then full wave rectified about 0 volts.

4. Anti-aliasing Filter:

This is a Krohn-Hite eight-order low pass Butterworth filter. The cut-off frequency is set at 2350 Hz. This is due to the fact that the signal will be sampled at a rate of about 4700 Hz in the index generation stage.

5. Index Generation:

The index generation section is based on an Intel 8085 microprocessor. The processor initiates 8 bit conversions of the analog signal at a rate of 4700 Hz. A total of 32,768 samples are taken and their average is calculated. This average (which is generated once every 7 seconds) is then transmitted to the HP–85 computer which stores them on a magnetic tape. The 7 seconds of averaging corresponds to half an hour of recorded geomagnetic signals, and thus this average value is the MA index of activity for that half hour period. The sampling at 4700 Hz implies that the highest frequency of our input to the index generation section should be 2350 Hz. However, this input comes from a nonlinear rectification process which generates high frequency components. As was explained previously, if we had a single sine wave of frequency f going into the full-wave rectification stage, then the spectrum of the rectified signal would consist of integral multiples of $2f$. If we consider only the $2f$ frequency, then it is clear that the input signal to the full-wave rectification stage should have frequency components of less than 1175 Hz. This corresponds to 4.55 Hz of the recorded geomagnetic signals. Consequently, our MA index of geomagnetic activity applies to frequencies of up to 4.55 Hz.

6. Recording of Indices:

The index values generated by the index generation stage are sent over to an HP–85 computer. The computer is used to store the index values on magnetic tape cassettes. These indices are then transferred to a VAX system for further processing. The HP–85 computer is also used to send sampling frequency information to the index generation system before playing back any tapes.

6. RESULTS

We ran a number of different tapes through our index generating system and obtained plots of the indices as a function of time. These results are presented in the following figures.

There are a few points about the figures that need to be explained. First, we note that the tape speeds and the speed up factor can not be exactly determined, since they change slightly during a playback session. Thus, at the end of a tape when the indices are plotted there will be a slight difference between the location on the plots where the indices stop and the mark on the axis where the last index is expected (assuming half hour per index). Thus, we matched the indices to the axis readings by slightly stretching the plots, if needed. This error is usually about an hour for a plot that covers about 5 days (less then one percent).

To understand the vertical axis of these plots, let us consider the operation of the analog to digital converter. The A/D converts an analog signal into 8 bits. Thus, the possible numbers are 0 to 255. In our case, the set up is such that -5V to +5V is covered by this range. Any input signal that is below -5V is converted to 0, and any signal above +5V is converted to 255. Our input signal is full-wave rectified and biased at -5V. Thus, our readings from the A/D are 0 to 255. However, in this set-up, after the full-wave rectified signal passes through the anti aliasing filter, we may get signals below -5V, and possibly signals above +5V, depending on the strength of the signals sampled. This introduces a nonlinearity in the system, since all the values above +5V are mapped to 255, and all the values below -5V are mapped to 0. Thus, for example, for a half hour index to be 255 would require all of the sampled values for that period to be +5V or more. We usually tried to keep this clipping to a minimum, but sometimes a need to achieve better resolution at low signal levels forced us to amplify substantially, thus, introducing clipping at large signal levels.

Consequently, the vertical axis is from 0 to 255 and is the half hour average of the sampled signals. These are the MA indices.

In most of the figures that follow, we have chosen to compare the MA index with the *ap* index. This is because, as explained earlier, the *ap* indices are 3-hour indices and so for every UT day we have eight points to compare with the 48 MA indices, whereas if we had used the daily *A* or *K* indices for our comparisons, we would have less informative plots: there would have been only one *A* or *K* index value per day. The information loss of going from the *ap* to *Ap* indices is due to two reasons. The first reason is the loss of information due to averaging of eight *ap* values to get one *Ap* value. The second reason is the *arbitrary* division of passage of time into UT days which creates various artifacts in the *Ap* plots, as will be demonstrated in Figure 11.

Let us begin with the first set of plots, shown in Figure 1. In this figure comparison is made between the MA index and the *ap* index (see description of this index in Appendix B) for the period of September 9 to September 16, 1963. It can clearly be seen that the MA index has a distinct daily variation in it, whereas the *ap* index has no such pattern. Thus, usually around 09–10 UT (02–03 local time) there is is a clear minimum in the extent of magnetic activity. Similarly, there is a maximum around 17–18 UT (10–11 local time).

Figure 2 shows a continuation of Figure 1. It covers the period of September 14 to September 21, 1963. It is interesting to note that the points in time where peaks of the MA index occur do not seem to correlate with the activity in the *ap* index.

Figure 3 is a further continuation of the previous figures. It covers the period of September 19 to September 26, 1963. Note that in this case there is a correspondence between the MA index and the *ap* index for the time when the *ap* index is very large. On the other hand, one can see the presence of daily variations of the MA index underneath the stormy patterns, whereas there is no daily variation in the *ap* plot.

Figure 4 further continues the previous figures. It covers the period of September 24 to October 1, 1963. Again one can see the daily variations of the MA index. But note the impulse of the MA index on approximately noon of September 28. This does not correspond to any significant *ap* activity.

Figures 5 and 6 show the discrete Fourier transforms of the previous MA indices. One can see in all of them that the magnitude of the frequency components corresponding to one day periods are the largest.

Figures 7 and 8 show two comparisons of the MA index plots that are attained when different filtering is used at the input stage to the index generation (see System Description). By comparing these plots the importance of being able to select various frequency bands becomes evident. For example, the stormy activity just prior to September 23 is almost completely confined to the less than 1.0 Hz frequency range. On the other hand, the impulsive activity around noon of September 28 is almost completely in the above 1.0 Hz frequency range.

Figures 9 and 10 show the discrete Fourier transforms of the filtered plots of Figure 8 and Figure 9. One obvious point is that it is in the 'low pass at 1.0 Hz' case where the daily variations have a strong magnitude. On the other hand, in the 'high pass at 1.0 Hz' case the resulting waveforms do not have any distinct frequency components. However, there is a decrease in the magnitude of the frequencies as one moves to higher frequencies.

Figure 11 is a copy of Figure 3 with an appended plot of the *Ap* indices. Here, we note that the *Ap* indices have a much smoother time variation than the *ap* indices (due to averaging). Note also how the strong geomagnetic activity peak around 0000 hours of September 23 is largely averaged out due to the fact that it falls in the middle of two geomagnetically quiet UT days. This figure clearly demonstrates the weaknesses of the *Ap* indices as real-time indicators of geomagnetic activity.

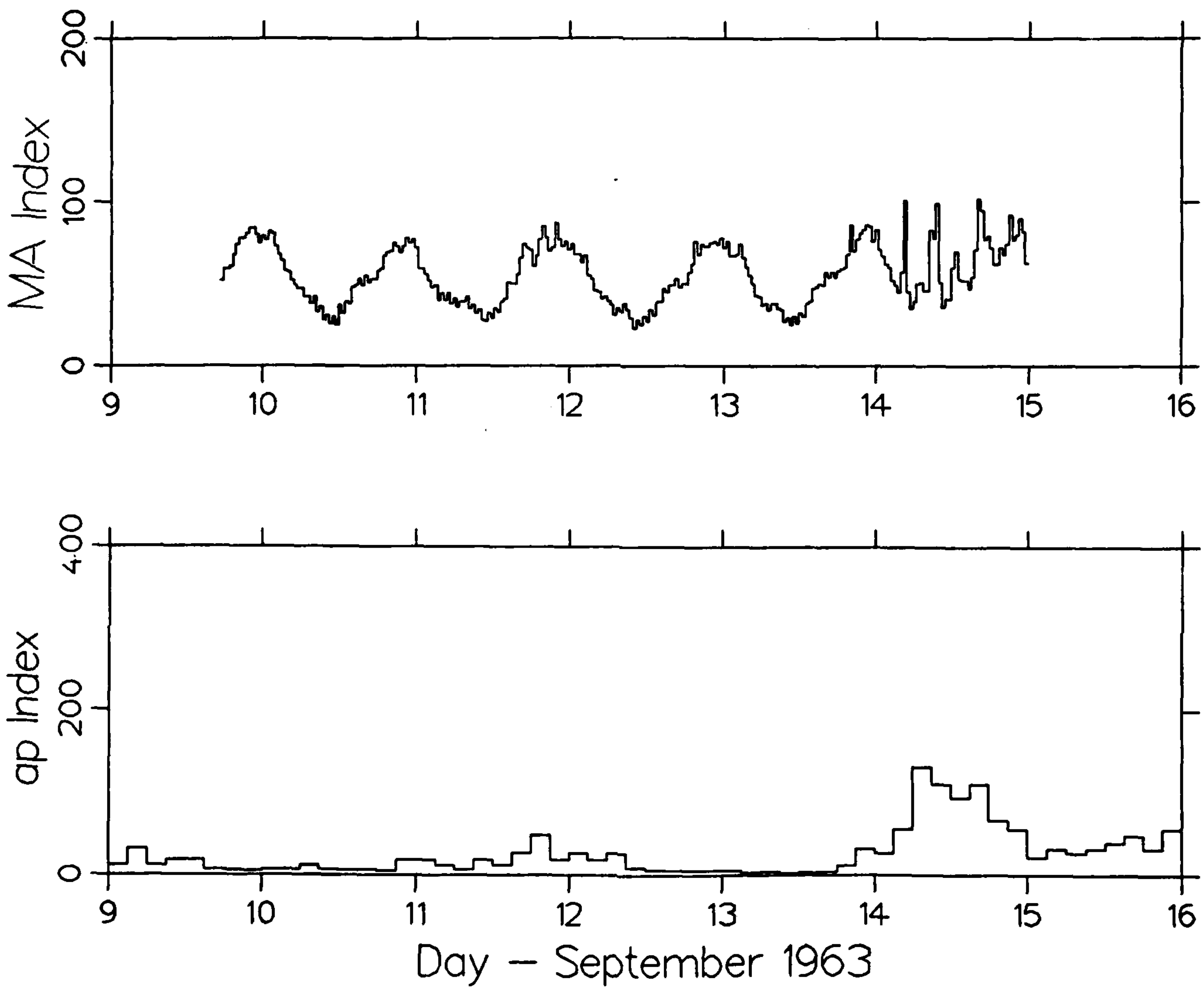


Figure 1. Comparison of the MA index with the *ap* index for the period of September 9 to September 16, 1963. The abrupt beginning and end of the MA index plot is due to using previously recorded tapes.

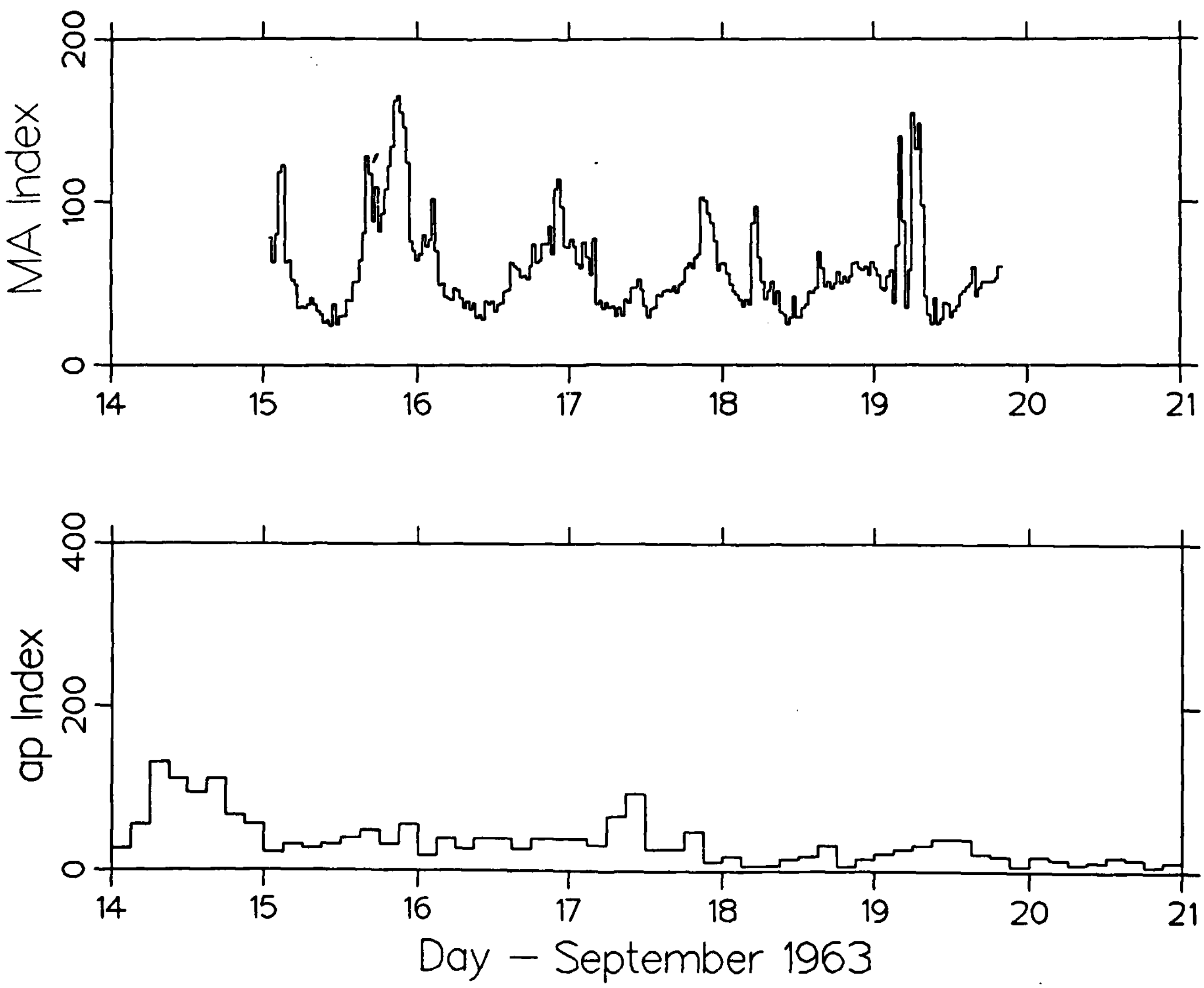


Figure 2. Comparison of the MA index with the *ap* index for the period of September 14 to September 21, 1963. The abrupt beginning and end of the MA index plot is due to using previously recorded tapes.

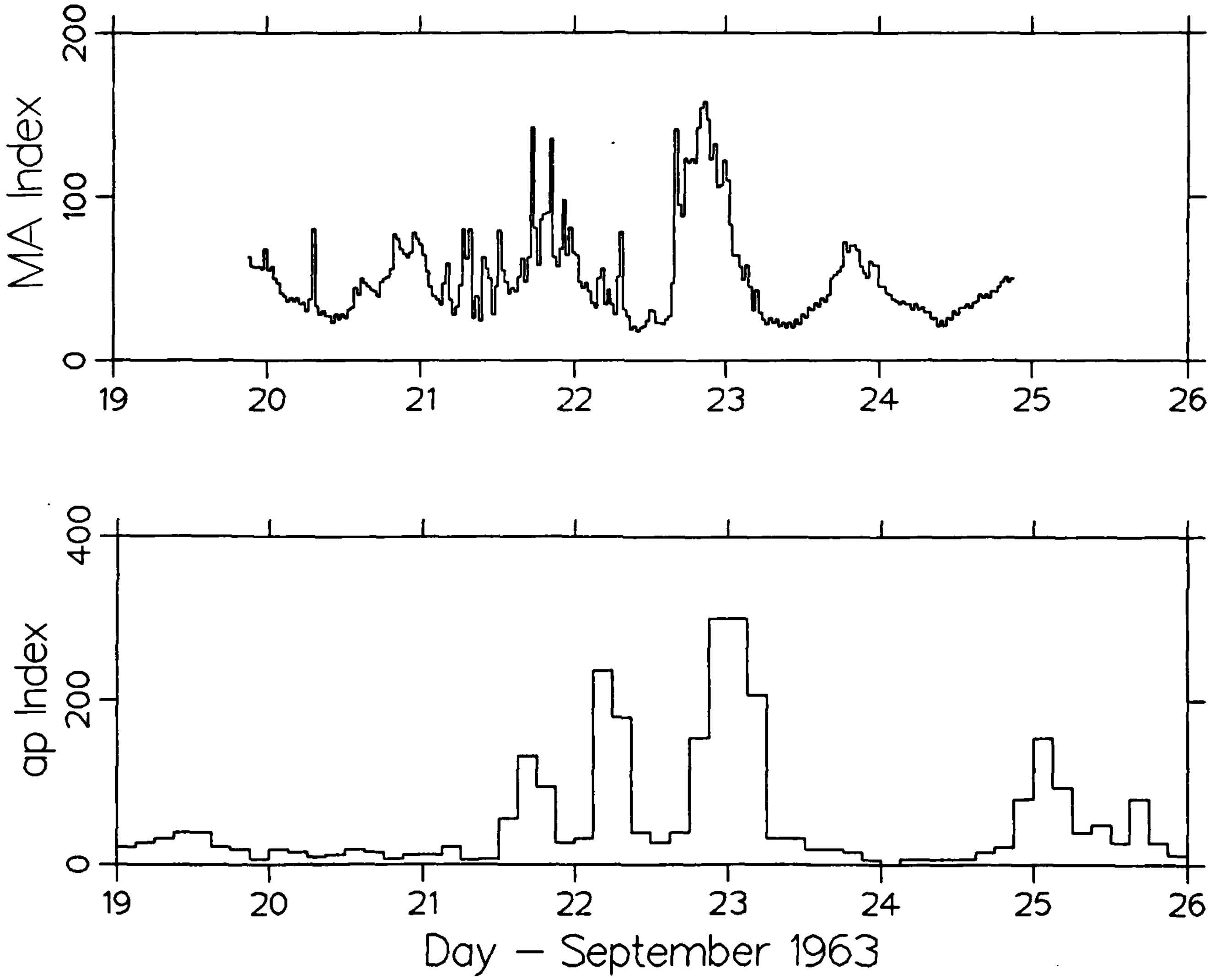


Figure 3. Comparison of the MA index with the *ap* index for the period of September 19 to September 26, 1963. The abrupt beginning and end of the MA index plot is due to using previously recorded tapes.

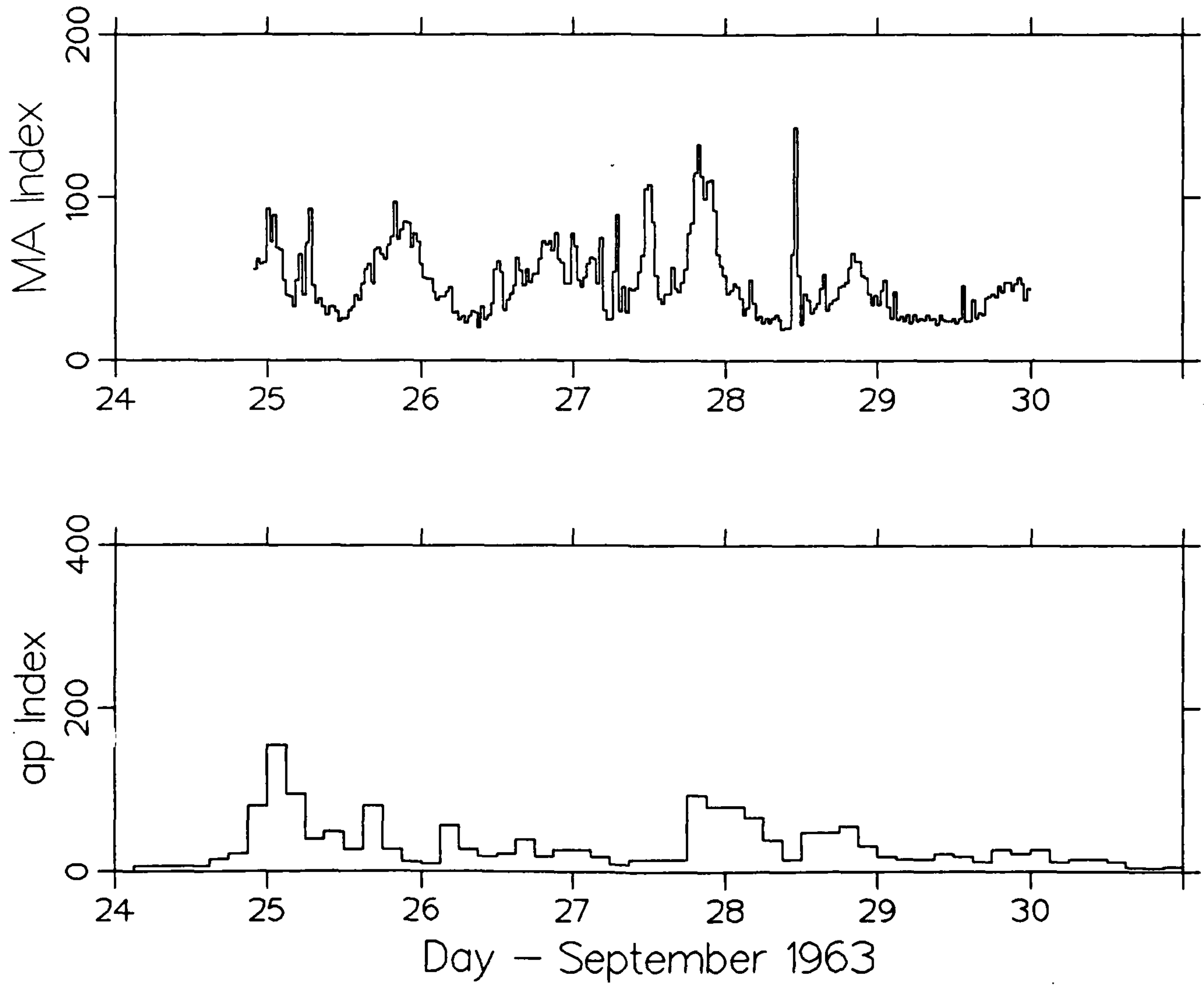


Figure 4. Comparison of the MA index with the *ap* index for the period of September 24 to October 1, 1963. The abrupt beginning and end of the MA index plot is due to using previously recorded tapes.

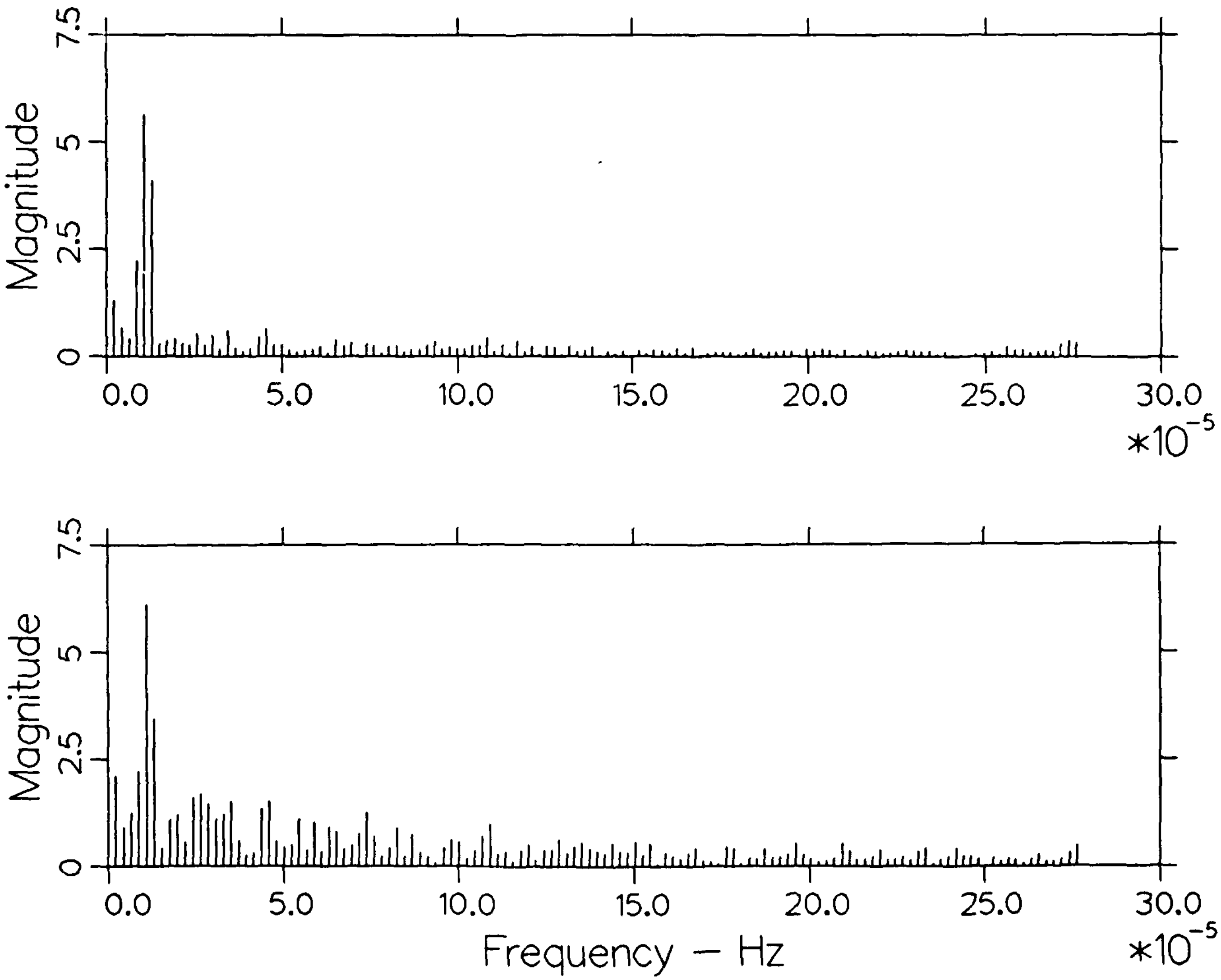


Figure 5. The magnitude of the discrete Fourier transform of the MA index of Figure 1 (upper plot), and that of the MA index of Figure 2 (lower plot).

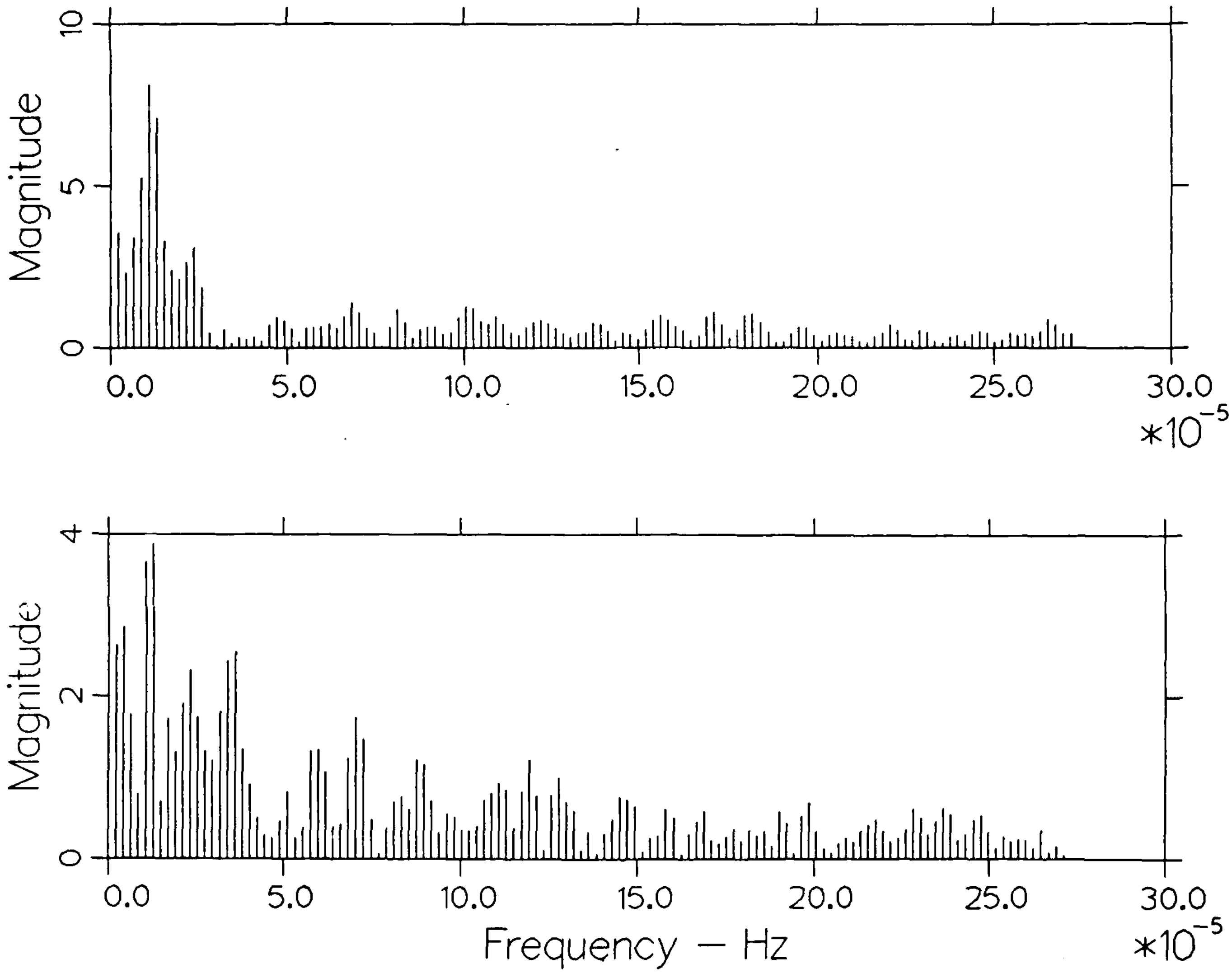


Figure 6. The magnitude of the discrete Fourier transform of the MA index of Figure 3 (upper plot), and that of the MA index of Figure 4 (lower plot).

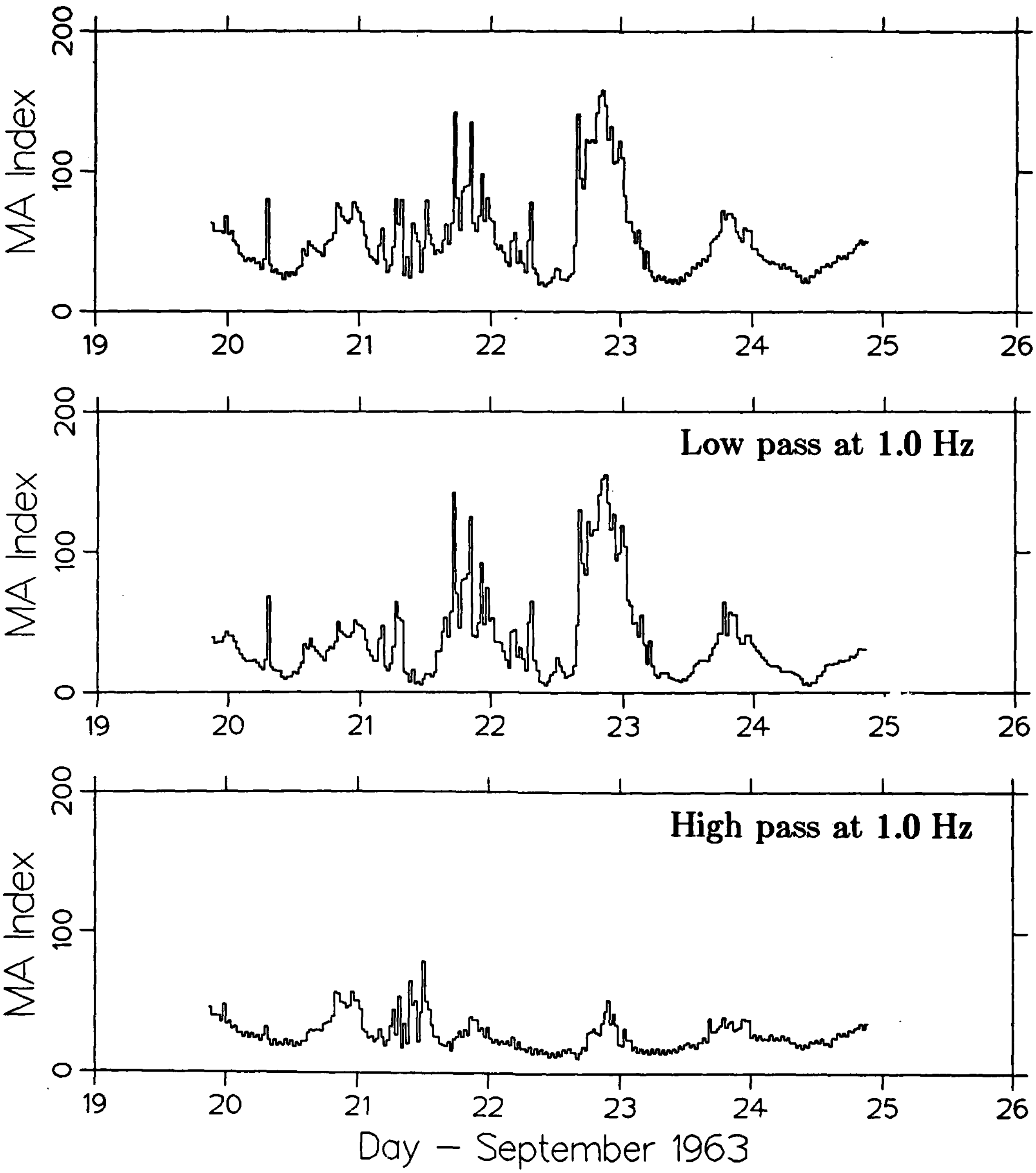


Figure 7. **Comparison of the MA index plots with various filters at the input for the period of September 19 to September 26, 1963. The plots are: no input filter (upper plot), low pass with cut-off at 1.0 Hz (middle plot), high pass with cut-off at 1.0 Hz (bottom plot).**

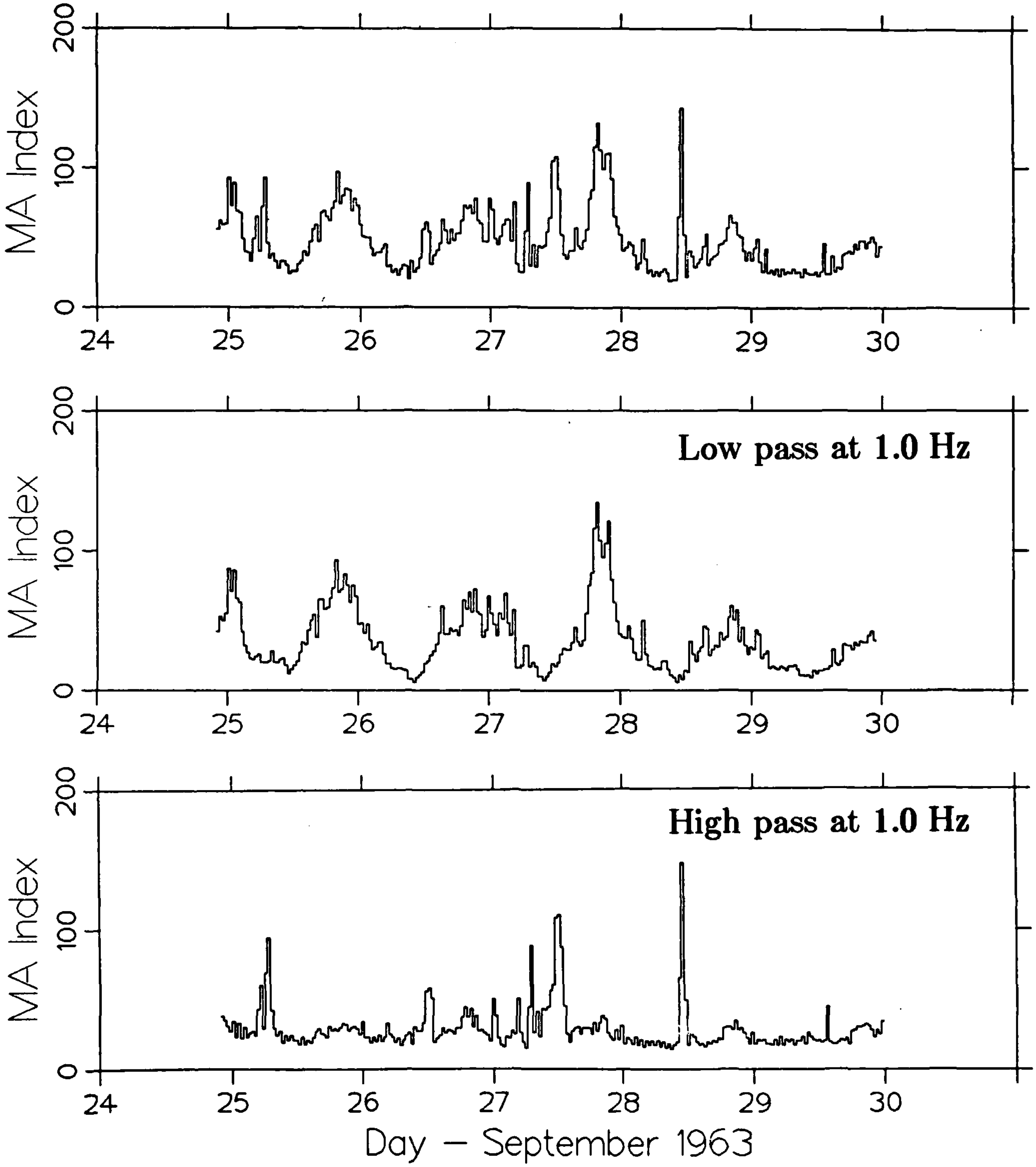


Figure 8. Comparison of the MA index plots with various filters at the input for the period of September 24 to October 1, 1963. The plots are: no input filter (upper plot), low pass with cut-off at 1.0 Hz (middle plot), high pass with cut-off at 1.0 Hz (bottom plot).

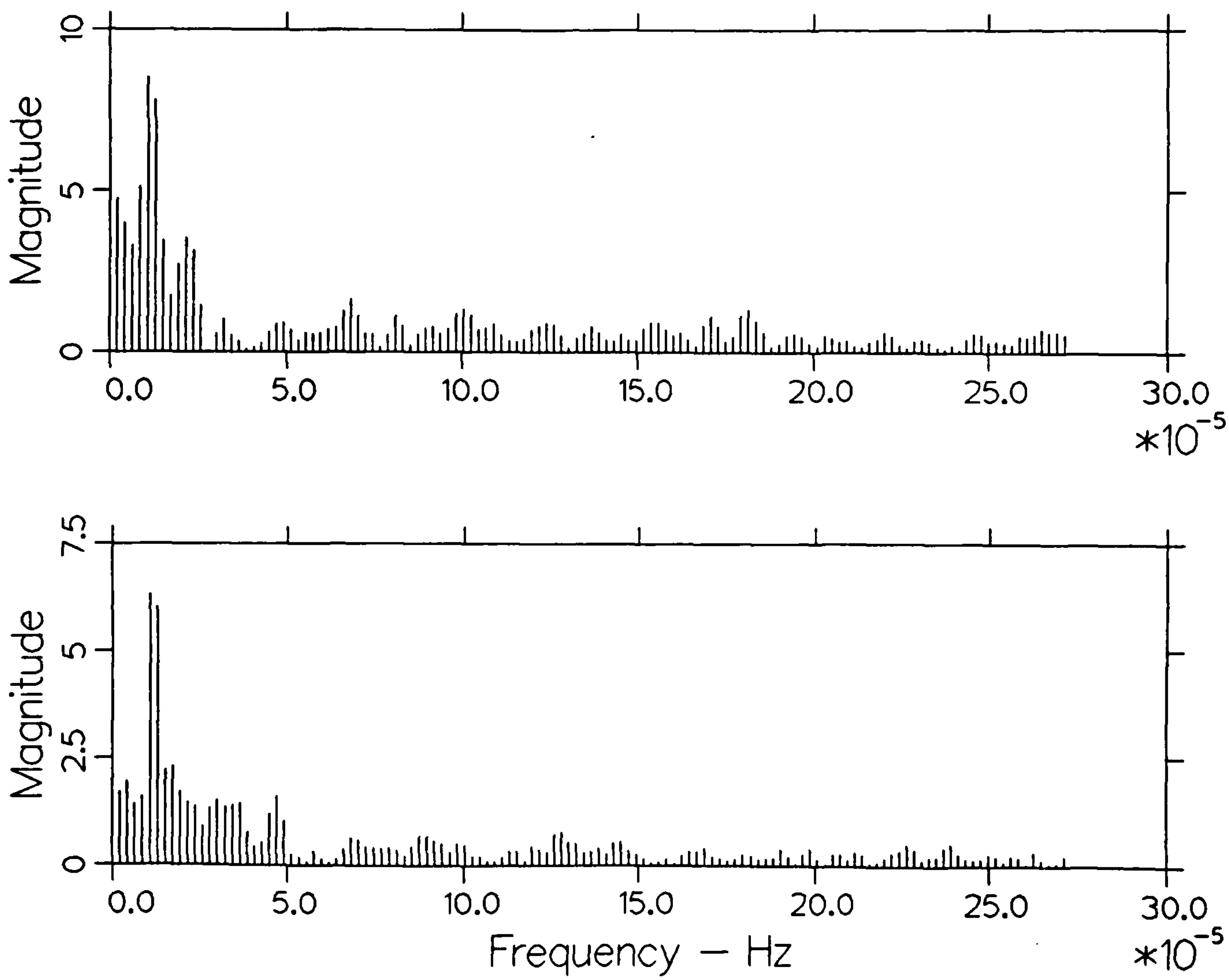


Figure 9. **The magnitude of the discrete Fourier transform of the low pass filtered MA index of Figure 7 (upper plot), and that of Figure 8 (lower plot).**

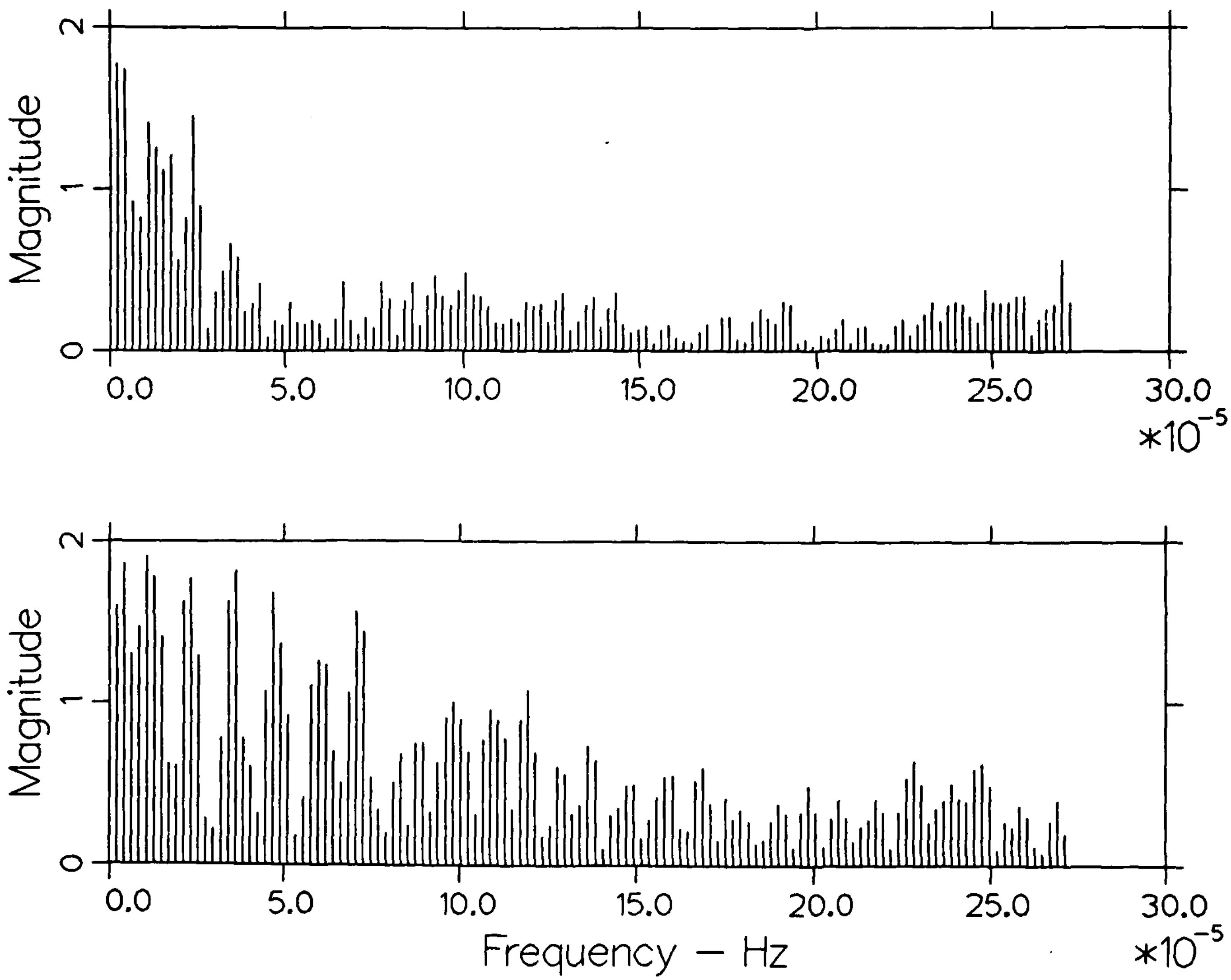


Figure 10. The magnitude of the discrete Fourier transform of the high pass filtered MA index of Figure 7 (upper plot), and that of Figure 8 (lower plot).

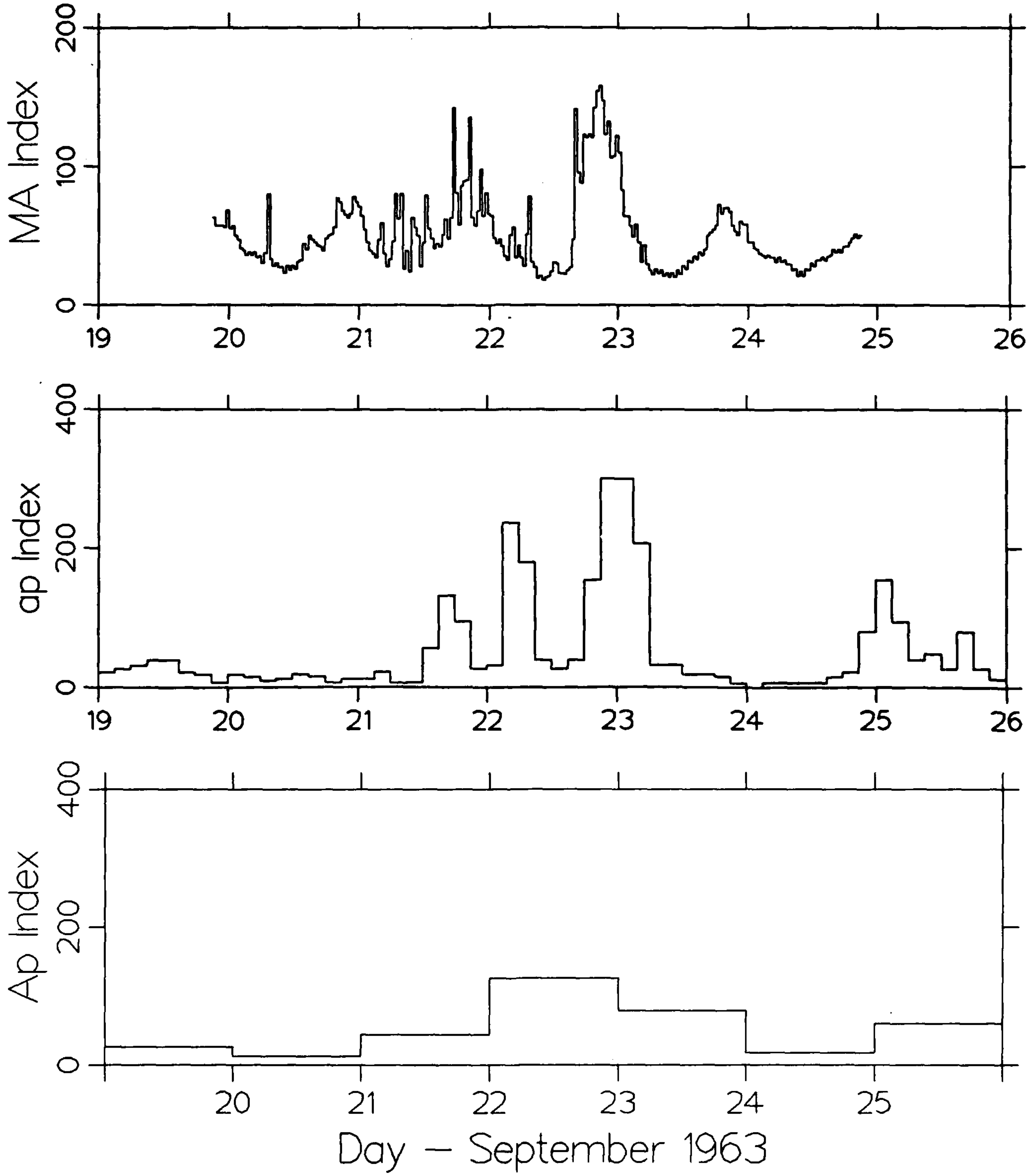


Figure 11. Comparison of the MA index with the *ap* and *Ap* indices for the period of September 19 to September 26, 1963. Note how the *ap* peaks (middle panel) are lost when the eight *ap* values per UT day are averaged to give the corresponding *Ap* index for the day (bottom panel).

7. CONCLUSIONS

We have described how an index of geomagnetic background noise (referred to as the MA index) can be derived for the M.A.D. frequency range, which covers the upper part of the conventional ultra low frequency range. We have presented the details of a single computer based system, which we have constructed, that implements the MA index. This index is a measure of the magnitude of band pass filtered geomagnetic activity up to a frequency of 4.55 Hz, and this upper limit is only due to hardware and software limitations and a higher upper limit may be achieved with an improved system.

We tested the system with previously recorded geomagnetic activity data. We observed that the MA index has a markedly different variations than the *ap* index for the same time intervals, and we saw the usefulness of having a filter at the input stage. The addition of a band pass filter at the input stage can significantly improve the detection of activity in specific Pc bands.

We have only tested this system with previously recorded tapes. The next step will be to set up a station at a field site and to configure the system to process real time data. We will have to modify various parameters of our system since there will be no speed-up factor involved. However, this change should not cause us any problems since we will be slowing down the whole system by about 250 times. Consequently, this will introduce extra time between the samples of the signal, and this extra time may be used to perform further processing of the data on site.

Thus, we expect to be generating real time MA indices, and these indices can then be sent over a telephone line to our laboratory's VAX computer for analysis. One problem which we may face in trying to implement the above test set-up is an inability of the HP–85 computer to continue the MA index generation activity while interfacing with a modem to transfer data across a phone line. This inability of the HP–85 is due to limitations of its memory size and processing power.

When we begin the real time generation of the MA indices we can further study their significance to the M.A.D. operations. We will also continue studying the time variations of the strength of the geomagnetic activity within the M.A.D. frequency band. By introducing various input filters we can isolate frequency bands where the geomagnetic background noise is at a minimum, and thus provide useful guidelines to the M.A.D. operators.

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APPENDIX A

In this appendix we give further details of the experimental set-up.

We first provide a block diagram of the architecture of the index generation system (Figure A1). The block diagram shows how the individual sections interact with each other, and also with the HP–85 computer. The analog geomagnetic signal is sent to the index generation system through input channel 0. This signal is the result of full-wave rectification of the output of the tape recorder, as was explained previously.

Secondly, we provide a photograph of the overall experimental set-up (Figure A2). This picture indicates the relative size of the equipment, and one can see that the system is compact enough to be easily moved to a field site for real time studies of geomagnetic activity.

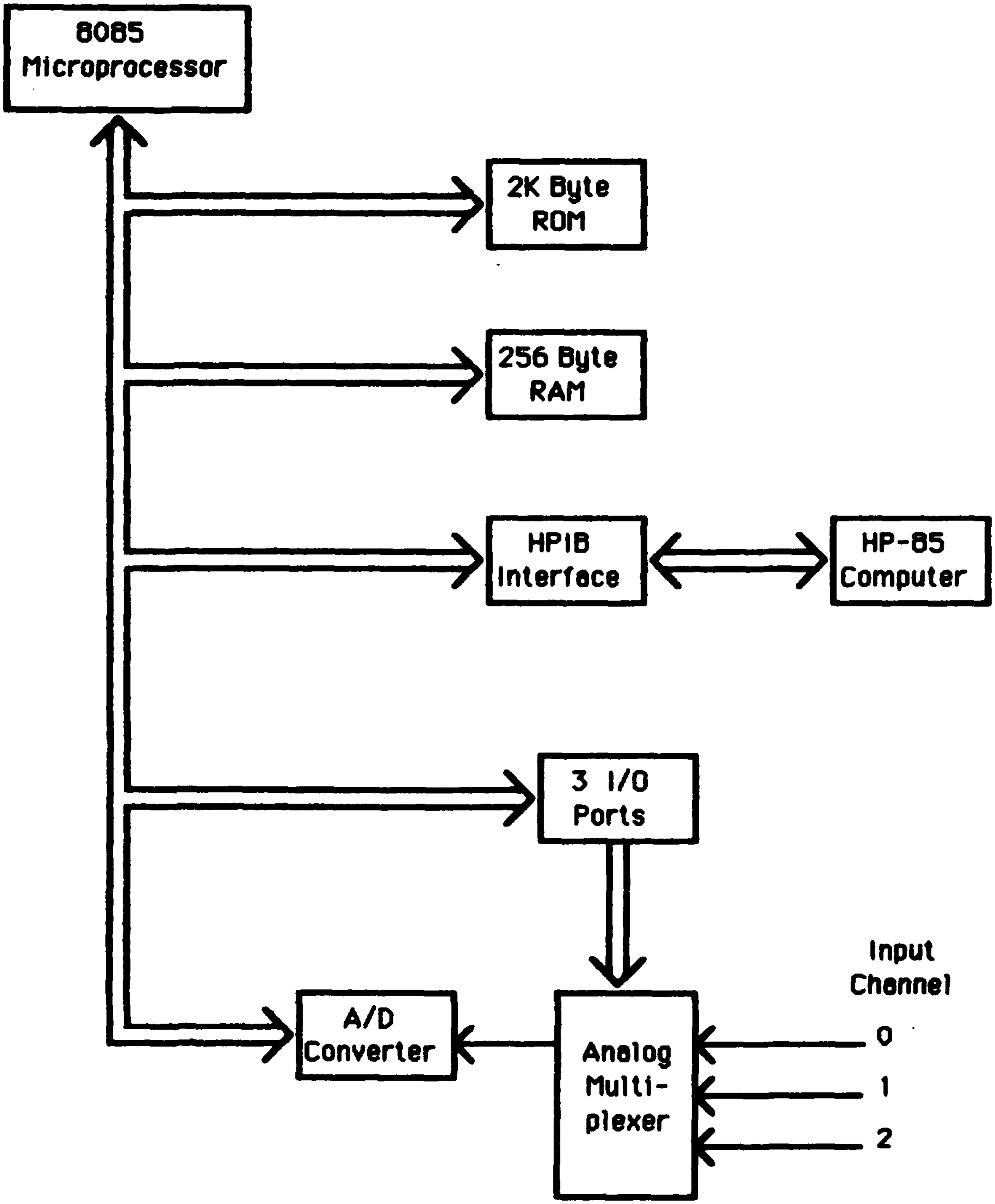

Figure A1. Architecture of the Index Generation System.

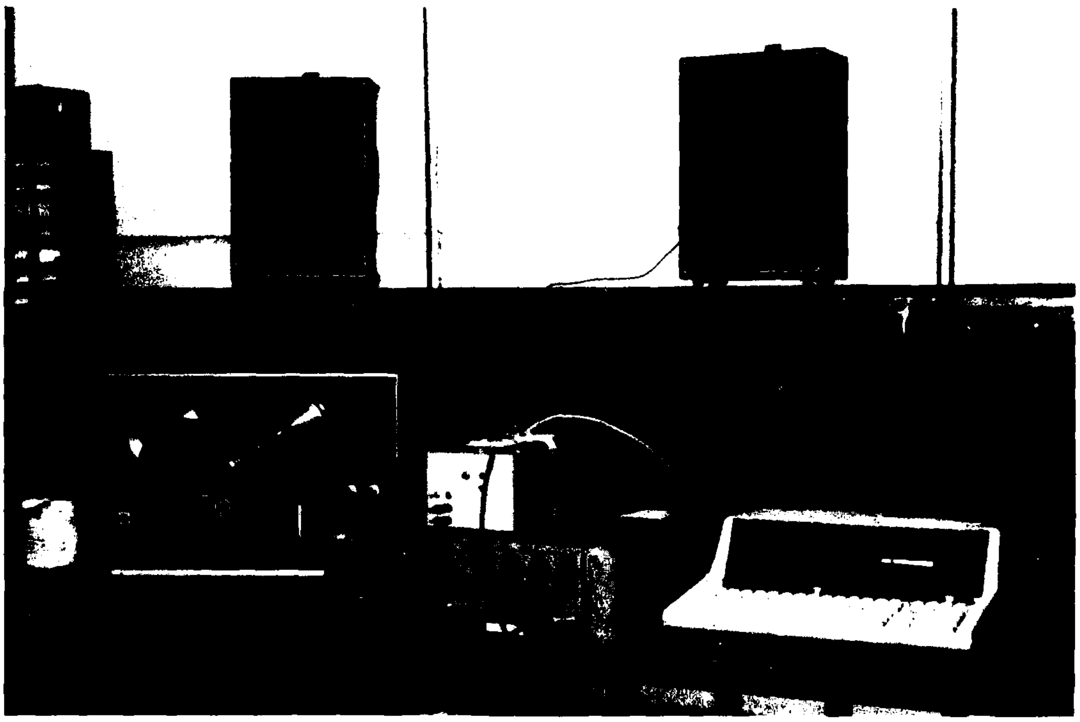

Figure A2. Photograph showing the overall experimental set-up. Note that the system is compact enough to be easily moved.

APPENDIX B

The following is the text of the paper "A proposed M.A.D. index of geomagnetic activity", by A.C. Fraser-Smith (Stanford University) and Otto Heinz (Naval Postgraduate School) that was presented at the First International Symposium of the Society of MAD-men, in Washington, D.C., during June 14-16, 1982.

A PROPOSED M.A.D. INDEX OF GEOMAGNETIC ACTIVITY

The U.S. Navy presently uses two versions of the *A* index of geomagnetic activity as indicators of natural noise in the frequency ranges used for its M.A.D. operations. One of these indices is the Fredericksburg *A* index (A_{Fr}), which is a measure of the geomagnetic activity occuring near Fredericksburg, Virginia, and the other index is the so-called planetary *A* index (Ap), which is a composite index derived from the geomagnetic activity measured at 12 locations around the world. Both indices are used extensively in geophysics to monitor the state of general geomagnetic activity and the progress of geomagnetic "storms" and other disturbances. When used this way, it is difficult to fault either index. Unfortunately, the indices were never intended to give a measure, or even an indication, of geomagnetic activity in the frequency range currently of interest in M.A.D. As a result, it is not uncommon for those involved with M.A.D. operations to observe strong activity in the M.A.D. frequency range when the indices are low, or little activity when the indices are high. The principal purpose of this paper is to show that, with modern technology, there is no reason for this situation to continue. Indices can now be derived quickly, and probably automatically, which will provide an accurate and nearly real-time measure of geomagnetic activity specifically in the M.A.D. bands. These indices can also be predicted ahead on both a short- and long-term basis by a variety of techniques that have already been developed. Finally, because the equipment required for the derivation of the indices should be compact and inexpensive, measurements can be made in each geographical region of operation, giving indices appropriate to those regions.

As described by *Lincoln* [1967], the *A* indices are daily indices that are derived by averaging the eight three-hourly *a* indices for each day. Each of the individual *a* indices is derived via a lookup table from a corresponding *K* index, which is a semi-logarithmic measure of the range of the variation of the magnetic field over the applicable three-hour interval. The *a* index is a linearized version of the corresponding *K* index, and as a rough rule of thumb it measures (in units of 2 gammas) the difference between the maximum and minimum excursions of the geomagnetic field in the three-hour interval. Each geomagnetic observatory can generate its own *a* indices and, because geomagnetic activity varies over the surface of the Earth, the *a* indices will generally differ between observatories. An attempt has been made to derive a worldwide, or planetary, *a* index, called the *ap* index, by averaging the *a* indices from 12 observatories distributed over the Earth's surface. The daily *A* indices are derived form the *a* indices by averaging the eight daily values. Thus, an *A* index can be generated either for a particular observatory - the A_{Fr} index for the Fredericksburg observatory in Virginia is a good example - or for the world - the *Ap* index - by taking the average of eight *ap* indices for the UT day. The *Ap* index so derived is often called the daily equivalent planetary index.

The unsuitability of the *A* indices for the M.A.D. work becomes evident when the details of their derivation are considered. As we have seen, the *a* indices that are averaged to produce the *A* indices are three-hour range indices, meaning that the upper and lower limits of variation of the geomagnetic field in a 3-hour interval are measured and the *A* indices are assigned according to the size of the *difference* between the upper and lower limits (*i.e.* according to the range of the variation during the 3-hour interval). This means that the indices are sensitive to the geomagnetic fluctuations covering a wide range of periods: not just the M.A.D. period range (roughly 0.5 - 25 sec), but a very wide range extending from periods of less than 1 sec down to periods as great as several hours, see Figure B1. Unfortunately, it is known that the amplitude of geomagnetic fluctuations varies approximately with frequency f as f^{-n}, with n in the range 1.0 - 1.3, which means that the amplitude of fluctuations increases as the frequency decreases, see Figure B2. It can be seen, therefore, that in a 3-hour interval it is activity with periods of an hour or more that largely determines the range of changes in the geomagnetic field, and that activity in the M.A.D. period range has little if any effect. Clearly, there can be no direct link between geomagnetic activity in the M.A.D. band and the *A* indices.

The fact that the *A* indices can be used at all, however unsatisfactorily, as indicators of activity in the M.A.D. band is the result of the correlations between the occurrences of the higher-frequency M.A.D. activity and the low-frequency activity that influences the *A* indices. These correlations do not ever appear to have been studied in detail, but it is known that both the M.A.D. band and the relevant low-frequency band include different varieties of geomagnetic pulsations, each with their own distinctive properties. It appears that some of these pulsations must (1) correlate, and (2) predominate in the two bands on occasion.

Given the remarkable computational power and speed of modern microprocessor-based minicomputers, there is no reason now why compact, automated, pulsation measuring stations cannot be established within each geographical region of relevance to the M.A.D., and geomagnetic activity specifically in the M.A.D. band measured continuously and converted to indices. There are a great variety of possible indices: they could cover whatever interval of time was to be considered most convenient for the M.A.D. operations, and they could measure amplitude ranges, (like the *A* indices) or possibly more appropriate quantities such as average power.

Recent work done by one of the authors has also demonstrated the possibility of predicting the indices on both a short-term (1-10 days) and long term (1-10 years) basis [*Fraser-Smith*, 1980, 1981]. By the use of these or other methods, preferably combined with an updating capability based on real-time solar flare occurance information, it should be possible to transmit both immediate and estimated future values of the M.A.D. indices to the users on a regular basis.

In summary, we propose eliminating the use of the *A* indices of geomagnetic activity in M.A.D. work, and their replacement by specifically-derived M.A.D. indices. These latter indices can be made much more appropriate to M.A.D. both in their frequency content and in their applicability to particular regions of operation. They can also be derived essentially in real-time, predicted ahead by known techniques, and updated as often as is needed. Finally, the cost of these changes should be small or negligible compared with the cost of M.A.D. operations.

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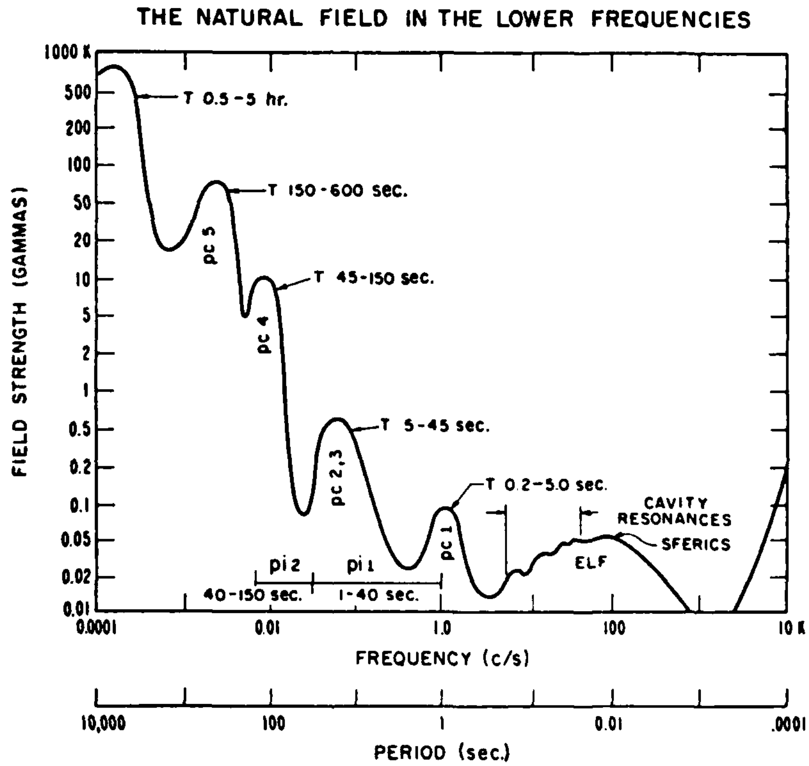

Figure B1. Showing the frequency dependence of the amplitudes of the geomagnetic field fluctuations at low frequencies [*Campbell*, 1966]. The variation shown is schematic, *i.e.*, it does not show an actual measured amplitude spectrum of the geomagnetic field variations.

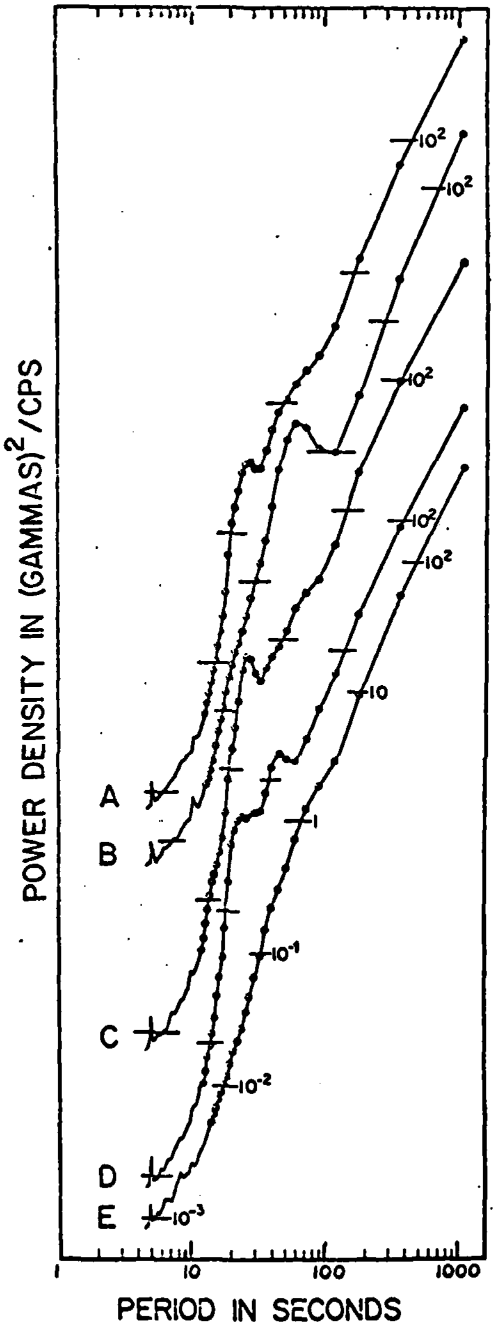

Figure B2. Actual measured power spectral densities of geomagnetic field fluctuations [*Davidson*, 1964].

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